Time course of homeostatic structural plasticity in response to optogenetic stimulation in mouse anterior cingulate cortex

Abbreviated title: Time course of homeostatic structural plasticity

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Abstract

Synaptic plasticity is the mechanistic basis of development, aging, learning and memory, both in the healthy and pathological brain. Structural plasticity is rarely accounted for in computational network models, due to a lack of insight into the underlying neuronal mechanisms and processes. Little is known about how the rewiring of networks is dynamically regulated. In our current study, we characterized the time course of neural activity, neural morphology, and the expression of synaptic proteins employing an *in vivo* optogenetic mouse model. We stimulated pyramidal neurons in the anterior cingulate cortex of mice and harvested their brains at 1.5 h, 24 h, and 48 h after stimulation. Stimulus-induced cortical hyperactivity persisted up to 1.5 h and decayed to baseline after 24 h, indicated by c-Fos expression. The synaptic proteins VGLUT1 and PSD-95, in contrast, were upregulated at 24 h and downregulated at 48 h, respectively. Spine density and spine head volume were also increased at 24 h and decreased at 48 h. This specific sequence of events reflects a continuous joint evolution of activity and connectivity that is typical of homeostatic structural plasticity. In this computational model, the turnover of dendritic spines and axonal boutons is regulated via firing rate homeostasis of individual neurons.

Introduction

Neural circuits in the mammalian brain are highly plastic. Functional plasticity means that chemical synapses change their strength by modifying signal transmission based on neurotransmitters and receptors (Bear and Malenka 1994; Malenka and Bear 2004). Structural plasticity, in contrast, refers to a variety of changes including the branching of dendrites, the geometry of dendritic spines, and number of dendritic spines and axonal boutons, and the connectivity between specific pairs of neurons (Caroni et al. 2012; Pfeiffer et al. 2018; Trachtenberg et al. 2002). Both forms of plasticity are underlying network assembly during development, use-dependent adaptation and learning in the adolescent and adult brain, but also network decay during aging and disease (Lamprecht and LeDoux 2004). Memory depends on plasticity. For instance, fear conditioning has been shown to increase both the synaptic strength and connection probability among a subgroup of granule cells in the dentate gyrus. The resulting memory engram encodes a distinct episodic memory (Ryan et al. 2015). Plasticity caused by injury, such as synaptic potentiation and network remodeling triggered by stroke or brain lesion, is likely to involve both activity perturbation and neuroinflammation (Keck et al. 2008; Murphy and Corbett 2009). In brain diseases, pathological plasticity may affect several brain regions. Acute and chronic stress, for instance, has been shown to induce different functional and structural alterations in the hippocampus, anterior cingulate cortex (ACC), amygdala (Lucassen et al. 2014), and elsewhere. Given this wealth of phenomena, the question arises how functional and structural plasticity is regulated.

The rules underlying experience-dependent plasticity need to be investigated further. Experiments in different brain regions with different plasticity-inducing paradigms have given rise to a host of different phenomena (Holtmaat and Svoboda 2009). Correlation-based Hebbian plasticity, summarized as “neurons that fire together wire together” (Hebb 1949), was proposed to account for homosynaptic strengthening observed in animals minutes to hours after artificial high-frequency stimulation (Lowel and Singer 1992). Despite its great potential in explaining learning and memory, Hebbian plasticity in computa-

tional network models was shown to increase the risk of excessive excitation or silencing, respectively (Miller and MacKay 1994; Sejnowski 1977). The same lack of network-level stability is implied by spike timing dependent plasticity (STDP), which implements either homosynaptic strengthening or weakening based on the relative timing of presynaptic and postsynaptic spikes (Bi and Poo 1998; Markram et al. 1997). The discovery of heterosynaptic plasticity and synaptic scaling, however, hinted that the modulation of a synapse may also depend on its neighbors (Chater and Goda 2020; Lynch et al. 1977) and the activity of the postsynaptic neuron (Turrigiano 2012). Chronic *in vivo* recordings have indeed revealed a robust cell-by-cell firing rate homeostasis across days and weeks (Hengen et al. 2016; Ma et al. 2019; Pacheco et al. 2019). New models of homeostatic plasticity (Turrigiano 2012, 2017), possibly in combination with Hebbian plasticity rules, are now being evaluated for their ability to solve the aforementioned network stability issues. Preliminary conclusions posit that the time scales of homeostatic control should be much faster than those observed in experiments (Zenke and Gerstner 2017). Rarely, however, was a possible role of structural plasticity explored in these theoretical studies.

Structural plasticity has been shown to occur jointly with functional plasticity. Changes in spine number and individual spine head volumes were observed after synaptic potentiation or depression *in vitro* (Engert and Bonhoeffer 1999; Matsuzaki et al. 2004; Zhou et al. 2004). Moreover, both spine density and synaptic strength were shown to compensate for input loss caused by entorhinal denervation in organotypic slice culture (Lenz et al. 2019; Vlachos et al. 2012). In parallel, theoreticians began to reflect over possible functional aspects of structural plasticity in a network (Fauth and Tetzlaff 2016). The homeostatic structural plasticity (HSP) model seems particularly promising in reconciling robust development and associative learning (Butz and van Ooyen 2013; Butz et al. 2009; Gallinaro et al. 2020; Gallinaro and Rotter 2018; Lu et al. 2019; Van Ooyen 2011). Still, the empirical data justifying such activity-dependent structural plasticity models are sparse. Most studies report changes in spine density after massive manipulation of activity, or in brain diseases, see review by Chidambaram et al. (2019). Unfortunately, time-resolved neural activity and connectivity was not included in any of them. Yusifov et al. (2021)

revealed the elaborate temporal dynamics of spine density during monocular deprivation but only apical dendrites were monitored. The time course of structural changes while the neuronal activity recovers, however, is of great importance to disambiguate structural plasticity models.

We adopted a mouse model previously developed in our laboratory, in which four days of optical activation of the ACC pyramidal neurons induced a transient depressive-like phenotype in the stimulated mice for a few days (Barthas et al. 2017, 2015; Sellmeijer et al. 2018). We sampled mouse brains at 1.5 h, 24 h and 48 h after chronic stimulation. We stained and quantified the relative abundance of neuronal activity marker c-Fos, and general synaptic markers the vesicular glutamate transporter 1 (VGLUT1) and the post-synaptic density scaffold protein PSD-95 (De Gois et al. 2005; Ehrlich et al. 2007). As expected, optogenetic stimulation triggered depressive-like behaviors and hyperactivity in mice (Barthas et al. 2015). Hyperactivity of pyramidal neurons, evidenced by a robust c-Fos expression at 1.5 h, eventually diminished to baseline 24 h after the end of the stimulation, while VGLUT1 and PSD-95 showed strong delayed upregulation at 24 h and again downregulated after 48 h in the stimulated mice. Similar to the temporal expression profile of VGLUT1 and PSD-95, dendritic spine density and spine head volume of the stimulated mice were increased at 24 h and restored to the control levels, or even slightly below control at 48 h. We also found that glial markers, GFAP and IBA1, were overexpressed throughout 48 h after stimulation. We will argue that, compared to other candidate theories, the homeostatic structural plasticity model could explain the biphasic changes of synaptic proteins and dendritic morphology consistently at 24 h and 48 h after the chronic stimulation.

Materials and Methods

Animals

3 – 5 months old genetically modified mice expressing ChR2 and yellow fluorescent protein (Thy1-ChR2-YFP) in a subset of pyramidal neurons (MGI Cat# 3719993, RRID:MGI:3719993) as well as C57BL/6J male adult mice (IMSR Cat#JAX:000664, RRID:IMSR_JAX:000664; Charles River, L'Arbresle, France) were used in the current study. All mice were kept in a reversed day-night cycle, with food and water provided *ad-libitum*. Mice were firstly group caged and then single housed after the optic fiber implantation. The Chronobiotron animal facilities are registered for animal experimentation (Agreement A67-2018-38), and protocols were approved by the local ethical committee of the University of Strasbourg (CREMEAS, n° 02015021314412082).

Animal experimental design

The animal experiments' objective was to determine the time course of plastic phenomenon triggered by external stimulation. We adopted an established optogenetics mouse model from our laboratory, in which the pyramidal neurons in ACC (24a/24b) were activated for four consecutive days (details see Optogenetic stimulation section below). We studied the temporal dynamics with discrete time points, by harvesting the mouse brain tissue at 1.5 h, 24 h, or 48 h after the last stimulation. As shown in our previous studies (Barthas et al. 2017, 2015), sustained stimulation of the ACC induces depressive-like behavior in naïve mice. So in the current study, we used splash test and novelty-suppressed feeding (NSF) test to verify the behavioral effects of the optogenetic stimulation. In the 24 h-post groups, we conducted splash test on the fifth day, while in the 48 h-post groups, we performed both NSF test and splash test on the fifth and sixth day and sacrificed the mice afterwards. We later evaluated the temporal evolution of neural activity by quantifying the expression of c-Fos at the three aforementioned time points. To capture when and where synaptic alterations may occur, the expression of pre- and postsynaptic proteins

were evaluated. Following the pattern shown by preliminary molecular screening, we examined if structural changes accompany molecular alterations by estimating the spine morphology of ACC pyramidal neurons harvested at 24 h and 48 h post-stimulation. To further confirm the involvement of glial cells, the expression of glial markers at 1.5 h, 24 h, and 48 h were respectively inspected. Before we performed all the experiments in Thy1-ChR2-YFP mice, we compared the efficacy of the transgenic approach with viral transfection. For the latter, we injected bilaterally AAV-CaMKII-ChR2 (H134R)-EYFP (Addgene plasmid #26969; `http://n2t.net/addgene:26969`; RRID: Addgene_26969) into the ACC (details see Virus injection section in the Supplementary Materials) of C57BL/6J mice. As we observed no differences in the c-Fos activity and behavioral outcomes in two approaches after optogenetic activation, we decided to perform all the experiments in transgenic mice to reduce the number of surgery that animals go through. All mice group information was summarized in Supplementary Table 1.

Stereotactic surgery

Stereotactic surgery was conducted to inject virus and implant optic fiber into ACC. During the surgery, mice were deeply anesthetized with a mixture of zoletil (25 mg/kg tiletamine and 25 mg/kg zolazepam) and xylazine (10 mg/kg) (Centravet, Taden, France; i.p. injection) and locally anesthetized by bupivacaine (Mylan, The Netherlands; 0.5 mg/mL; subcutaneous injection, 1 mg/kg). The coordinates of the injection/implantation site are +0.7 mm from bregma, lateral: ±0.3 mm, dorsoventral: −1.5 mm from the skull (Barthas et al. 2015; Sellmeijer et al. 2018).

Optic fiber implantation

We inserted 1.7 mm-long LED optic fiber (MFC_220/250-0.66_1.7mm_RM3_FLT, Doric Lenses, Canada) unilaterally (left or right) in C57BL/6J mice two weeks after the virus injection or directly in naïve Thy1-ChR2-YFP mice. The fiber was inserted into ACC for 1.5 mm deep with reference to the skull. The metal end was fixed onto the skull by

superglue and dental cement, and then the skin was stitched. For stimulation, we used blue light (460 nm wavelength) and the light intensity of optic fibers used in the current study ranged from 1.7 mV/mm^2 to 6 mV/mm^2.

Optogenetic stimulation

After the optic fiber implantation, we individually housed the mice to avoid possible damage to the implant. After seven days of recovery, we started the optogenetic stimulation protocol on freely moving mice in their home cages. Optogenetic stimulation took place on four consecutive days for 30 min. Stimulated mice received repetitive stimuli sequences of ten seconds consisting of eight seconds at 20 Hz with 40 ms pulse duration and two seconds without stimulation. We did not observe the effects of light on the behaviors in gene-matched wild type mice (Supplementary Figure 1-2). So we used transgenic mice for all experiments and kept the light off for the sham groups. At the end of stimulation, all mice were handled again and unplugged from the cable.

Behavioral tests

We performed all the behavioral tests during the dark phase under red light. Splash test (Nollet et al. 2013) and novelty-suppressed feeding (NSF) test (Samuels and Hen 2011) were used to evaluate depressive-like behaviors. In the splash test, we sprayed 15% sucrose solution onto the coat of the mice and recorded the total grooming time for each mouse during the following 5 min. The NSF test was conducted on a different day of splash test and we removed the food pellets 24 h before testing. During the test, we put each mouse into an open field, where a food pellet was placed in the middle, and recorded the time delay necessary for each mouse to touch and eat the pellet (within 5 min).

Verification of injection site and tissue harvesting

Mice were perfused with cold 4% paraformaldehyde (PFA) in 1× phosphate buffer (PB, 0.1 M, pH 7.4), under Euthasol Vet (intraperitoneal injection, 2 μL/kg; TVM, UK) over-

dose anesthesia. The details of timing and pump speed can be found in the Supplementary Materials. Frontal sectioning of the brains (40 μm-thick for immunohistochemical staining and 300 μm-thick for microinjection) was performed on a vibratome (Leica-VT1000s, Rueil-Malmaison, France). The injection or implantation site of each perfused mouse was checked under the microscope.

Immunohistochemical staining

We did fluorescent staining to examine the expression of c-Fos, VGLUT1, PSD-95, Neurogranin, and GFAP (see Supplementary Table 2 for the antibody concentrations). We used sections ranging from 1.42 mm to -0.23 mm away from Bregma, with a distance 160 μm in between. The sections were firstly washed in 1× PBS (3×10 min) and then blocked at room temperature (RT) with 5% donkey serum in 0.3% PBS-T (1 h). Later the sections were incubated at 4 °C with corresponding primary antibody and 1% donkey serum in 0.3% PBS-T overnight. Sections were rinsed with 1× PBS (3×10 min) in the next morning, incubated with secondary antibody in 0.3% PBS-T at RT (2 h), and rinsed again with 1× PBS (3×10 min). Sections were mounted on gelatin-coated slides, air-dried, and coverslipped with Vectashield H-1000 (Vector Laboratories, Germany).

We stained IBA1 with 3, 3′-Diaminobenzidine (DAB, Sigma, US). Sections were selected, washed, blocked, and treated with primary and secondary antibodies as described above. Then the sections were rinsed with 1× PBS (3×10 min) and incubated with avidin–biotin–peroxidase complex (ABC Elite, Vector Laboratories, Germany; 0.2% A and 0.2% B in 1× PBS) at RT (1.5 h). Later the sections were rinsed with 0.05 M Tris-HCl buffer (TB; pH 7.5; 3×10 min). Peroxidase revelation was achieved by incubation shortly (20 s) with a mixture of 0.025% DAB and 0.0006% H_2O_2 in 0.05 M TB. Sections were carefully rinsed with TB (2×10 min) and 1× PBS (2×10 min) to cease the reaction. All sections were mounted and air-dried, then dehydrated in graded alcohol baths (1×5 min in 70%, 1×5 min in 90%, and 2×5 min in 100%), cleared in Roti-Histol (Carl Roth, Germany), and coverslipped with Eukitt.

Microinjection

We used microinjection and confocal microscope (Dumitriu et al. 2011) to visualize and quantify the neural morphology at 24 h and 48 h post-stimulation. The sections were selected within the distance of approximately ± 0.4 mm anterior-posterior (AP) away from the optic fiber. The injection was done only into the pyramidal neurons from layer $2-3$ of ACC (24a/24b) from both hemispheres. The injection pipettes were pulled from glass capillaries with filament, with a final resistance around 150 MΩ. We filled the pipette with red fluorescent dye solution Alexa 568 hydrazide (#A10441, Thermo Fisher, USA) in filtered $1\times$ PBS ($1:40$). We performed microinjection under the microscope of a patch-clamp set-up. During injection, we penetrated the pipette tip into the soma and switched on the current to -20 pA to drive the dye diffusion for 20 min. Later we switched off the current but left the pipette tip inside the soma for another 5 min to fill the dendrite and spines. All the sections were retrieved and covered with Vectashild H-1000 (Vector Laboratories, Germany) for confocal microscope imaging. We checked all the injected neurons for YFP signal; only neurons with YFP signal were identified as pyramidal neurons and selected for further analysis.

Microscope imaging

To analyze the morphological features, we took z-stacked images of microinjected neurons (with step size 0.2 μm-0.3 μm sampled by the software Leica SP8 LAXS 3.5.6) with confocal microscope Leica SP8 (Leica Microsystems, Germany). Whole neuron structure were imaged with objective HC PL APO CS2 $63\times/1.40$, with pixel resolution 0.2 μm per pixel. If not stated otherwise, for excitation we used a pulsed laser (White Light; 488 nm). The dendrite segments, from apical and basal dendrites of each neuron, were imaged with objective HC PL APO CS2 $63\times/1.40$ as well, but with pixel resolution 0.05 μm per pixel. Secondary to third level dendrite segments with less overlap and clear background were selected.

To quantify the expression of c-Fos, VGLUT1, PSD-95, neurogranin, and GFAP in the

ACC, we imaged epifluorescent signals of stained sections with Morpho Strider on Zeiss Imager2 (Carl Zeiss, Germany) with 2.5× objective and pixel resolution 0.35 μm per pixel. To achieve better resolution of representative images, we also imaged the sections at the middle focal plane with a confocal microscope Leica SP8 (Leica Microsystems, Germany; software Leica SP8 LAXS 3.5.6) with objectives HCX PL Fluotar 5 × /0.15 and HC PL APO CS2 63 × /1.40, with pixel resolution 0.5 μm and 0.2 μm per pixel, respectively. The bright-field images of DAB-stained IBA1 were acquired with a NikonEclipse E600 microscope with 4× and 40× objectives (MBF Bioscience, USA; software Neurolucida 2019), with pixel resolution 0.1 μm and 2.0 μm per pixel.

3D reconstruction and analysis of dendritic morphology

Firstly, after imaging, we deconvolved our confocal z-stack images with Huygens Professional 19.04 (Scientific Volume Imaging, The Netherlands) to restore the object from the acquired image through knowledge of the point spread function (PSF) and noise. 3D reconstruction and morphological analysis were later performed on the deconvoluted images.

For each pyramidal neuron, we reconstructed the soma and its dendritic tree with Imaris 9.5.1 (ImarisXT, Bitplane AG, Switzerland). Based on the reconstructed data, the dendritic tree structure was represented by Sholl intersections (Sholl 1953) at different radiuses. The order of each dendrite segment and its corresponding length and average diameter were also estimated. We further used Fiji (ImageJ, Fiji) to measure the soma size of each neuron on its z-projected image.

We reconstructed the dendritic shafts and spines with Imaris 9.5.1 again for selected dendrite segments at high resolution. We also classified the spine classes (filopodia, long-thin, stubby, and mushroom) based on their morphological features with the Imaris Spines Classifier package. The criteria of spine classification were summarized in Supplementary Table 3. We harvested the overall spine density of each segment and the spine density of each spine class based on the reconstructed data. The spine head volume of individual

spines was also estimated.

Quantifying immunohistochemical staining images

Visually inspection showed the expression of marker proteins was not homogeneously distributed in ACC but constrained to the vicinity around the optic fiber. To reflect such a pattern, we systematically analyzed the expression of c-Fos, VGLUT1, PSD-95, Neurogranin, GFAP, and IBA1 in both hemispheres at different distances to the optic fiber at 1.5 h, 24 h, and 48 h post-stimulation.

We firstly organised the corresponding epifluorescent images (obtained under 2.5× objective) or bright-field images (obtained under 4× objective) of each marker for each mouse in sequential order. The Bregma level of each section was identified in reference to the Mouse Brain Atlas (Franklin et al. 2008). Later we checked the implantation site for each section. Sections with a clear trace of implantation were marked as *distance zero*. Sections at a more anterior position than the distance zero were labeled with a negative sign (−), while posterior sections were labeled with a positive sign (+). In the end all sections were classified into five distance groups and their average distances were noted as −0.4 mm, −0.2 mm, 0 mm, +0.2 mm, and +0.4 mm. Both hemispheres were also carefully identified as the ipsi- or contralateral side in reference to the implantation site.

To quantify the signal intensity of markers on each section, we created two same-sized masks (700 μm × 700 μm) on both hemispheres with Fiji. For c-Fos and IBA1, we counted signal positive cell numbers within each section's masks, while for VGLUT1, PSD-95, neurogranin, and GFAP, we quantified the fluorescent intensity within the masks. The quantified fluorescent intensity or cell count at each discrete time point were respectively normalized by the averaged intensity or cell count from the ipsilateral side of the *zero distance* sections of the sham mice.

For Neurogranin, in addition to the overall signal intensity, we also quantified its relative intensity in soma to infer its cellular translocation. Sections within 0.1 mm anterior-posterior to the optic fiber were selected. We first drew the shape of soma and measured

its fluorescent signal intensity and area size. Then we moved the mask to the neighboring area around the soma and measured the fluorescent intensity of the same-sized area as a reference. Five random selections were measured in the adjacent regions and averaged to serve as the reference. We normalized the signal intensity of soma by the signal intensity of its neighboring area as the relative soma intensity.

Statistical analysis

We have different types of data in the current study, non-clustered independent data and nested data. Independent measurement, such as behavioral data, was contributed only once by each mouse. We used the non-parametric Mann Whitney U test to examine if the optogenetic stimulation triggered significant behavioral alterations.

Some datasets, such as the signal intensity of immunohistochemical staining and the neural morphology, are highly nested. In the staining experiments, each mouse contributed multiple brain sections in five distance groups; for the morphological data, each mouse contributed several neurons, and each neuron further contributed multiple dendrite segments. In such conditions, using multiple measurements from each mouse as independent measurements artificially inflates sample size N and risks our study for achieving inappropriate conclusions. Indeed, we observed highly significant results for all quantified data obtained in IHC and microinjection experiments, when applied tests such as Mann Whitney U test or Kruskal Wallis test (Supplementary Materials: Comparing LMM with other tests). We therefore used a more conservative analysis, linear mixed effects model (LMM) in R (R Core Team 2019), to assess the effects of stimulation, while accounting for the nested residual structure. We used the lme4 package (Bates et al. 2015) and applied glmer function (GLMM) to model cell counting data. Our null hypothesis is that there is no significant difference between the sham and the stimulated mice, neither between the ipsi- and contralateral hemisphere of each mice. So in the model, we set the main effects of stimulation, implantation site, and their interaction effects as fixed effects. On the other hand, neuron ID, animal ID, and distance level are random effects

(Zuur et al. 2009). Three discrete time points were separately analyzed. All models were checked in terms of homogeneous and normally distributed residuals, using diagnostic plots. We further checked final models for over-dispersion. Detailed model structures and the model selection and validation processes were described in the Supplementary Materials. All the R scripts of LMM and GLMM could be found under the following link: `https://github.com/ErbB4/LMM-GLMM-R-plasticity-paper`

The significance of fixed effects was tested by extracting effect strengths of each parameter, including their confidence intervals; $p < 0.05$, $p < 0.01$, and $p < 0.001$ were used to indicate 95% CI, 99% CI, or 99.9% CI of the estimated coefficient does not cross zero. If not stated otherwise, $*$ denoted the main effect of optogenetic stimulation (sham/stimulated), # denoted the main effect of stimulation side (ipsi/contra to the optic fiber). Significant interaction effects were not denoted but stated in the main text. "n.s." denoted neither main effects nor interaction effects were significant.

Neuron, synapse, and network models

Numerical simulations of networks with homeostatic structural plasticity were used as a framework to interpret the outcome of our various measurements in mouse experiments. We used the same neuron model, synapse model, and network architecture, as published in our previous paper on transcranial electric stimulation (Lu et al. 2019). All the plastic neuronal network simulations of the current study were performed with the NEST simulator using a MPI-based parallel configuration (Linssen et al. 2018).

The current-based leaky integrate-and-fire (LIF) neuron model was used for both excitatory and inhibitory neurons. We employed an inhibition-dominated recurrent network with 10 000 excitatory and 2 500 inhibitory neurons to represent the local network of ACC (Brunel 2000). All neurons in the network receive Poisson drive at a rate of $r_{\text{ext}} = 30\,\text{kHz}$ to reflect external inputs. All connections involving inhibitory neurons in this network were established randomly with 10% connection probability and then kept fixed. Only excitatory to excitatory (E-E) connections were subject to homeostatic structural plastic-

ity (HSP) (Gallinaro and Rotter 2018; Lu et al. 2019). Each excitatory neuron monitors its own firing rate using its intracellular calcium concentration and grows or retracts its spines and boutons to form or break synapses (Figure 7A, see Supplementary Materials for details). Initially, the network has no E-E connections at all, but spontaneous growth goes on until an equilibrium between network activity and structure is reached. In this equilibrium state, the E-E connectivity is at 9%, and all excitatory neurons fire around the rate of 8 Hz imposed by the controller. Spiking activity is generally asynchronous and irregular. Detailed parameters of the neuron model, synapse model, and network model can be found in Supplementary Tables 4, Table 5, and Table 6. The methods employed to measure neuronal activity and connectivity in numerical experiments are described again in more detail in the Supplementary Materials.

Modeling optogenetics

Optogenetics uses microbial opsin genes to achieve optical control of action potentials in specific neuron populations (Yizhar et al. 2011). In our current study, we used humanized channelrhodopsin-2 (hChR2), a fast light-gated cation-selective channel, to depolarize mouse pyramidal neurons (Nagel et al. 2003). The kinetics of ChR2 activation is a complicated light-dark adaptation process: Light activates and desensitizes the channels, while they recover in the dark phase (Bruun et al. 2015; Zamani et al. 2017). These state transitions have been studied in detail in computational models of ChR2 (Nikolic et al. 2013; Williams et al. 2013). It did not seem necessary, however, to include the detailed kinetics of ChR2 in our large spiking neural network with homeostatic structural plasticity. To reduce the complexity of the model and save computational power, we conceived optogenetic stimulation as an extra Poisson input of rate $r_{\text{opto}} = 1.5\,\text{kHz}$ and weight $J_{\text{opto}} = 0.1\,\text{mV}$. Neurons responded with an increased firing rate to this stimulation, as observed in optogenetic stimulation experiments.

Numerical experimental design

In mouse experiments, the ACC of animals were optogenetically stimulated for four consecutive days at the same time, with a duration of 30 min per day. In our computational model, we started the optogenetic stimulation after the network had reached its structural equilibrium. To avoid excessively long simulation time, we accelerated the remodeling process by employing relatively fast spine and bouton growth rates, see Figure 2 of Gallinaro and Rotter (2018) for details. The relative duration of stimulation vs. relaxation was left unchanged, however. Since the optogenetic stimulation in experiments activates a large fraction of all pyramidal neurons in ACC, we chose to stimulate half of the excitatory neurons ($f_{\mathrm{opto}} = 50\,\%$) in the model. All the model parameters are summarized in Supplementary Table 7.

Results

Optogenetic activation of ACC (24a/24b) pyramidal neurons triggered cortical hyperactivity and behavioral alterations

To study the time course of neural structural plasticity, we adopted the optogenetic mouse model previously published in our laboratory (Barthas et al. 2017, 2015) in which we repetitively activated ACC pyramidal neurons for four days. We firstly compared the viral transfection and transgenic approaches (Supplementary Figure 1-1A-E). We previously showed with the transgenic approach that there was an increased c-Fos expression at 1.5 h after the stimulation (Barthas et al. 2015) and here we also reproduced the results with viral injection approach (Supplementary Figure 1-1F-G; Figure 1G, left panel). Besides the cortical hyperactivity, both approaches induced a depressive-like phenotype in mice at 24 h and 48 h post-stimulation (Supplementary Figure 1-1H-I; Figure 1E-F) as published before. To avoid double surgeries, we decided to continue with transgenic mice throughout the current study. We also confirmed that light did not trigger behavioral alterations (Supplementary Figure 1-2).

In two other batches of transgenic mice, we also examined the c-Fos expression at 24 h and 48 h post-stimulation and observed no difference between the stimulated and sham mice (Figure 1G, middle and right panels). These data suggested that optogenetic stimulation triggered hyperactivity in the ACC was restored to baseline level at 24 h and 48 h post-stimulation.

To capture the temporal evolution of neural plasticity, we stimulated transgenic Thy1-ChR2-YFP male adult mice and harvested their brains at 1.5 h, 24 h, and 48 h post-stimulation for further experiments (Figure 1A-C). Mice used for immunohistochemical staining experiments showed depressive-like behaviors at 24 h and 48 h post-stimulation, as shown by decreased grooming behaviour in splash test and increased latency to eat in the NSF test (Figure 1D-F). All mice group information and experimental design were summarized in Supplementary Table 1.

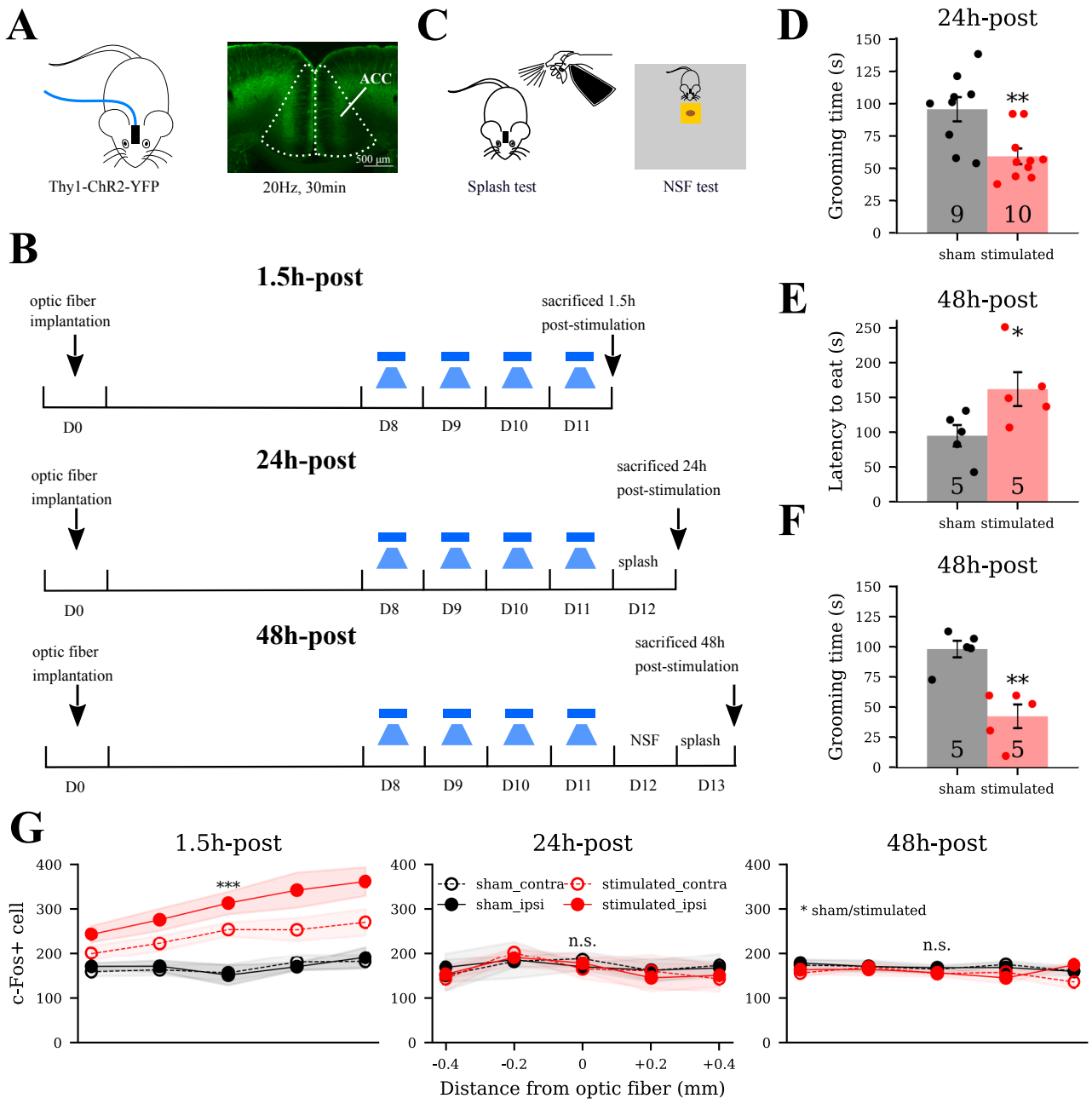

Figure 1: Consecutive optogenetic stimulation triggered hyperactivity in ACC and depressive-like behavior in mice. **A-C** Experimental design of the current study. **D-F** Mice used for immunohistochemical staining experiments showed depressive-like behavior at 24 h and 48 h post-stimulation. **D** Splash test results of mice sacrificed at 24 h post-stimulation ($p = 0.003$, Mann Whitney U test; $N = 9$ for sham, $N = 10$ for stimulated). **E-F** Results of NSF and splash tests for mice sacrificed at 48 h ($p = 0.01$ and $p = 0.005$, Mann Whitney U test; $N = 5$ for sham, $N = 5$ for stimulated mice). **G** c-Fos expression was elevated by the optogenetic stimulation at 1.5 h ($p < 0.001$) and specifically on the ipsilateral side ($p < 0.01$), decayed to baseline at 24 h and 48 h post-stimulation. The x ticks label the mean distance of stained sections (−, anterior; +, posterior) from the optical fiber. The y axis labels the c-Fos+ cell number within the masks of stained sections. GLMM was used for the statistical analysis. $p < 0.05$, $p < 0.01$, and $p < 0.001$ means 95% confidence interval (CI), 99% CI, and 99.9% CI does not cross zero respectively.

VGLUT1 and PSD-95 in ACC showed time-dependent regulation by optogenetic stimulation

To capture if, when, and where plasticity were induced by optogenetic stimulation, we used immunohistochemical staining to anchor the expression pattern of two widely-used synaptic proteins: VGLUT1 and PSD-95. We estimated the expression of both proteins in the ipsi- and contralateral hemispheres of ACC sections with reference to the hemisphere where the optic fiber was implanted, at 1.5 h, 24 h, and 48 h (Supplementary Table 1). Frontal-sectioned brain slices in both sham and the stimulated mice were organized based on their distance away from the optic fiber.

The representative fluorescent staining of VGLUT1 was organized by distance and by time in Supplementary Figure 2-1. Intensity quantification summarized in Figure 2A-B showed that optogenetic stimulation did not trigger significant alteration at 1.5 h (95% CI $= [-0.083, 0.070]$, LMM), while significant upregulation was observed in the stimulated mice compared to sham mice at 24 h (99% CI $= [0.009, 0.477]$, LMM). Further examination of interaction effects confirmed stronger upregulation in the ipsilateral side (99.5% CI $= [-0.344, -0.116]$, LMM) in the stimulated mice. At 48 h, no more significant difference was detected between the stimulated and sham mice (95% CI $= [-0.012, 0.138]$, LMM). Our data at discrete time points suggested that optogenetic stimulation altered VGLUT1 expression in a time-dependent manner. Indeed, the upregulation was observed after 1.5 h, peaked around 24 h, and returned to baseline at 48 h post-stimulation, while the stimulation effects were constrained to areas around the optic fiber.

Similar expression pattern was observed with PSD-95 staining (Supplementary Figure 2-2, Figure 2C-D). At 1.5 h, no significant changes were induced by the stimulation (95% CI $= [-0.051, 0.018]$, LMM). At 24 h, enhanced expression of PSD-95 in ACC was observed in the stimulated mice (95% CI $= [0.008, 0.55]$, LMM) and specifically in the ipsilateral hemisphere (99.5%CI $= [-0.335, -0.109]$, LMM). At 48 h, although the effect size was small, the PSD-95 expression of the stimulated mice declined to a lower level than sham (99% CI $= [-0.171, -0.005]$, LMM). Our data suggested a similar time-dependent

manner of PSD-95 upregulation as VGLUT1 after the optogenetic stimulation: upregulation at 24 h and downregulation at 48 h.

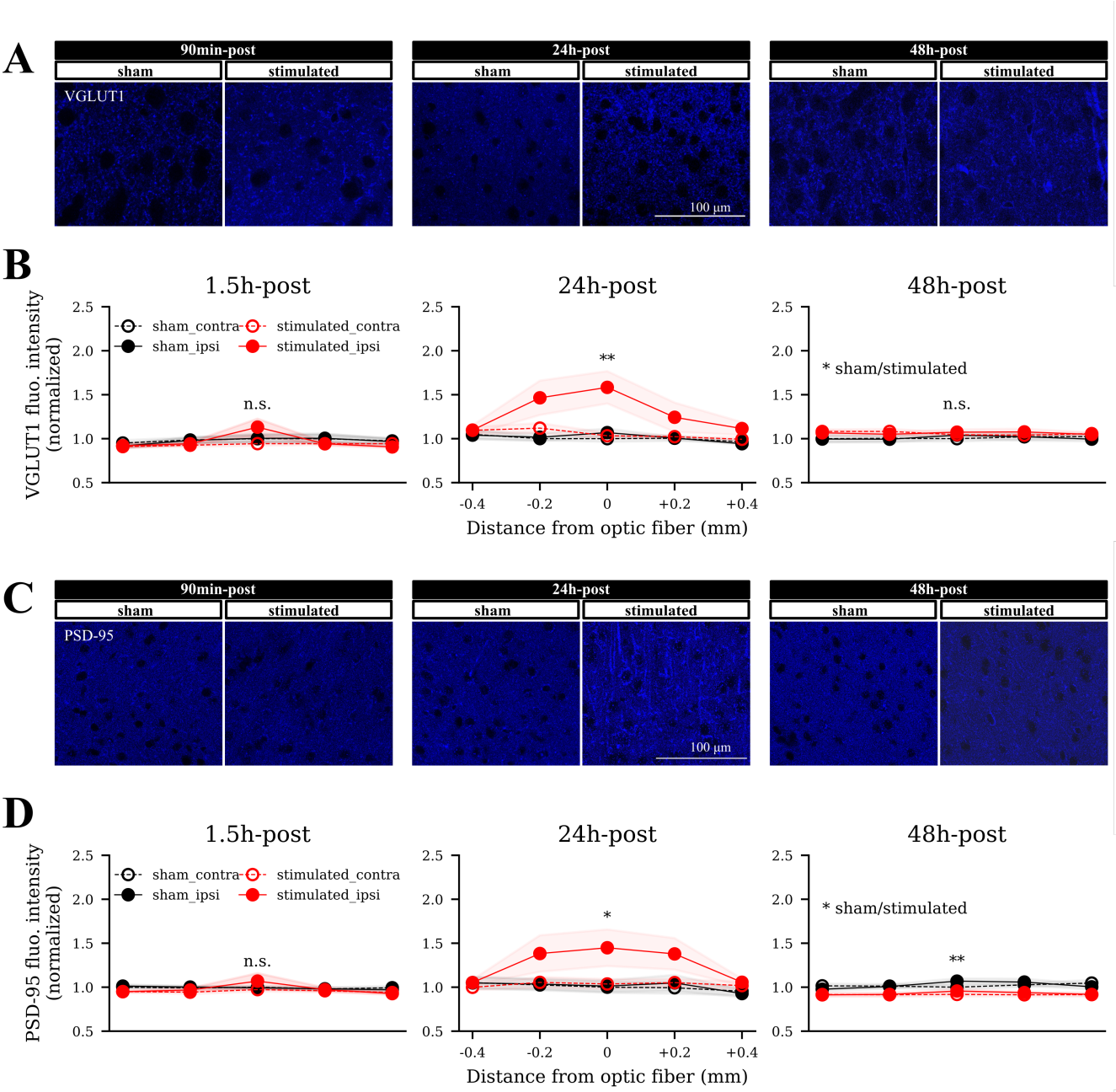

Figure 2: Expression of VGLUT1 and PSD-95 were upregulated by optogenetic stimulation at 24 h and decayed at 48 h post-stimulation. **A, C** Representative images of VGLUT1 and PSD-95 staining on the ipsilateral hemisphere of sections within 0.1 mm anterior-posterior (AP) to the optic fiber from both sham and stimulated mice. **B** Normalized VGLUT1 fluorescent intensity at different time and distance to the fiber optic. The main effect of optogenetic stimulation (sham/stimulated) was significant at 24 h. **D** The PSD-95 fluorescent intensity at different time and distance. At 24 h, the main effect of stimulation was significant. At 48 h, main effect of stimulation was significant.

Neurogranin was not upregulated by optogenetic stimulation

Since PSD-95 is expressed in the postsynaptic membrane of glutamatergic synapses in both excitatory and inhibitory neurons (Zhang et al. 1999), we studied another postsynaptic protein, neurogranin, which is exclusively expressed in the pyramidal neurons (Singec et al. 2004). Despite the fact that the same type of quantification and analysis procedures were applied to neurogranin stained ACC sections, no time-dependent or side-dependent alterations of neurogranin was observed (Supplementary Figure 3-1, Figure 3A-B; 95% CI = $[-0.111, 0.031]$, 95% CI = $[-0.170, 0.277]$, 95% CI = $[-0.102, 0.266]$, respectively, LMM).

Considering that neuronal stimulation could drive the translocation of neurogranin from soma to dendrites (Huang et al. 2011), we suspected that the optogenetic stimulation might fail to trigger neurogranin upregulation but induced the cellular translocation. Consequently, we selected sections within 0.1 mm anterior-posterior to the optic fiber and quantified the relative fluorescent intensity of neurogranin in the soma (Figure 3C-D). Pyramidal neurons from the three sham groups all showed a high soma concentration. After the stimulation, the relative signal intensity of soma was slightly increased at 1.5 h ($p < 0.001$, Mann Whitney U test), decreased to a level lower than 1 at 24 h ($p < 0.001$, Mann Whitney U test), and recovered to a level above 1 but lower than the sham group at 48 h ($p < 0.001$, Mann Whitney U test). These data suggested that the optogenetic stimulation may not trigger neurogranin upregulation, but induce translocation with time: concentrated in soma at 1.5 h, translocated away from soma at 24 h, and recovered at 48 h.

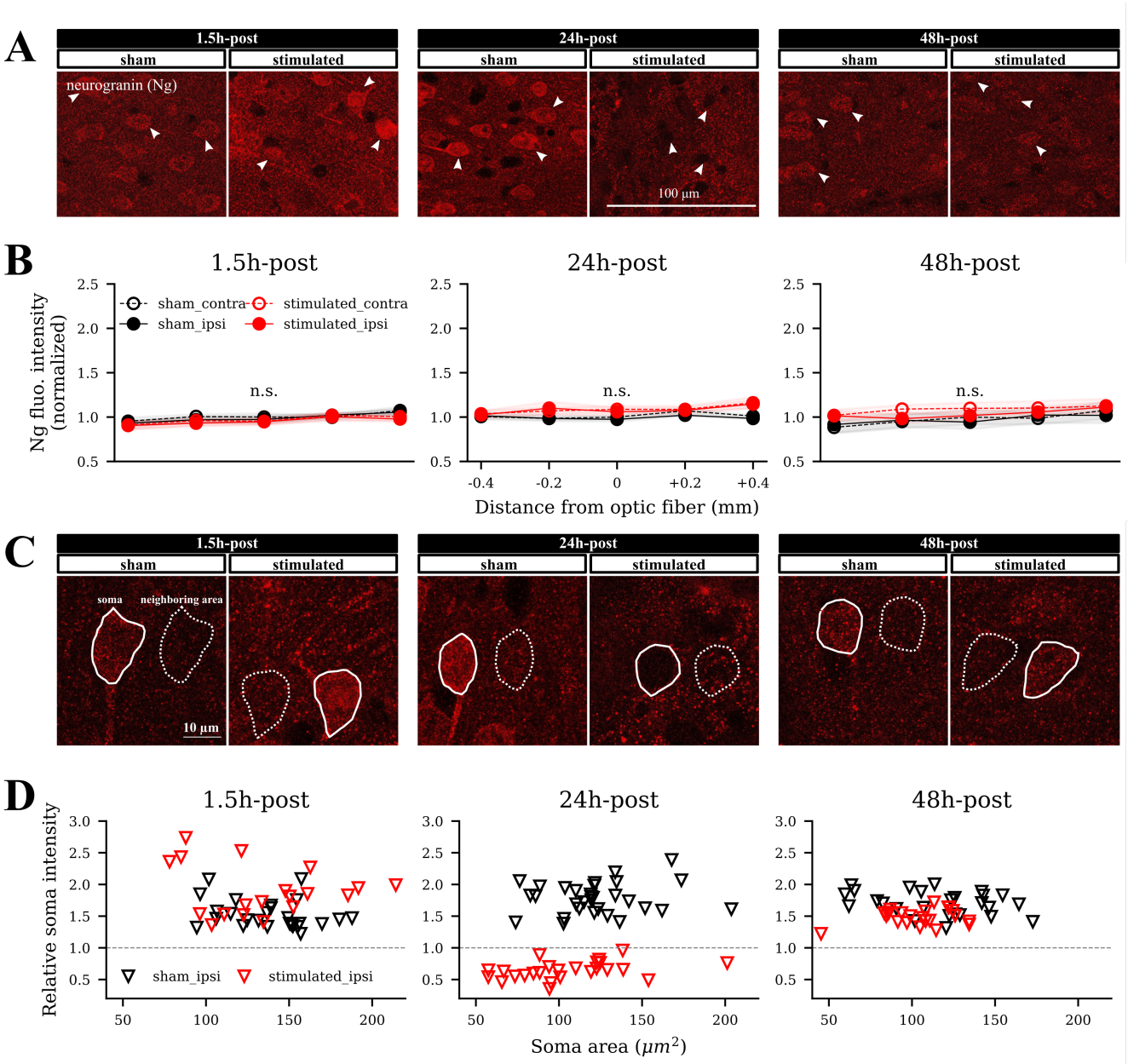

Figure 3: Optogenetic stimulation failed to alter the expression of neurogranin, but may trigger its cellular translocation. **A** Representative images of neurogranin staining on the ipsilateral hemisphere of sections within 0.1 mm anterior-posterior to the optic fiber from both sham and stimulated mice. White arrowheads indicate the soma of pyramidal neurons. **B** In terms of fluorescent intensity, no significant effects were observed between stimulated and sham mice (LMM). **C** Representative images of neurogranin distribution in soma and region around soma. White solid and dashed lines indicate the soma or the neighboring area respectively. **D** The scatter plots of soma area and its relative intensity of neurogranin at 1.5 h, 24 h, and 48 h. The relative intensity in the neural soma for sham mice was all above 1. The relative intensity of neural soma from stimulated mice was slightly increased at 1.5 h, greatly dropped below 1 at 24 h, and recovered to a level lower than sham at 48 h ($p < 0.001$, $p < 0.001$, $p < 0.001$, respectively, Mann Whitney U test).

Dendritic tree structure was not drastically affected by optogenetic stimulation at 24 h and 48 h

The gross analysis of the expression of VGLUT1, PSD-95, and neurogranin suggest synaptic changes on the ipsilateral side in sections close to the optic fiber from the stimulated mice, at 24 h and 48 h after the stimulation. Thus we wondered if such changes are accompanied by neural morphological alterations.

We then stimulated mice the same way as described above and harvested their brains at 24 h or 48 h post-stimulation. As shown in Figure 4A, mice showed depressive-like behavior as expected ($p = 0.004$ for 24 h-post group, $p = 0.012$ and $p = 0.006$ for 48 h-post group, Mann Whitney U test). We injected red fluorescent dye (Alexa 568) into pyramidal neurons selected from the area around the optic fiber to visualize and analyze the neuronal morphology.

Neural dendritic structure at 24 h and 48 h was visualized as in Figure 4B. Pyramidal neurons from both ipsi- and contralateral ACC were collected (Figure 4C). The soma size and dendritic tree structure evaluated by Sholl intersections were not changed by the optogenetic stimulation (Figure 4D-E). No remarkable changes were detected in neither dendritic length nor average dendritic diameter, except that some dendritic segments showed a reduction or increase in dendritic diameter (Supplementary Figure 4-1). Our data suggested, except for local dendrite diameter changes, no drastic dendritic tree structure and soma size inflation or shrinkage of pyramidal neurons in the vicinity of the optic fiber were induced by the optogenetic stimulation.

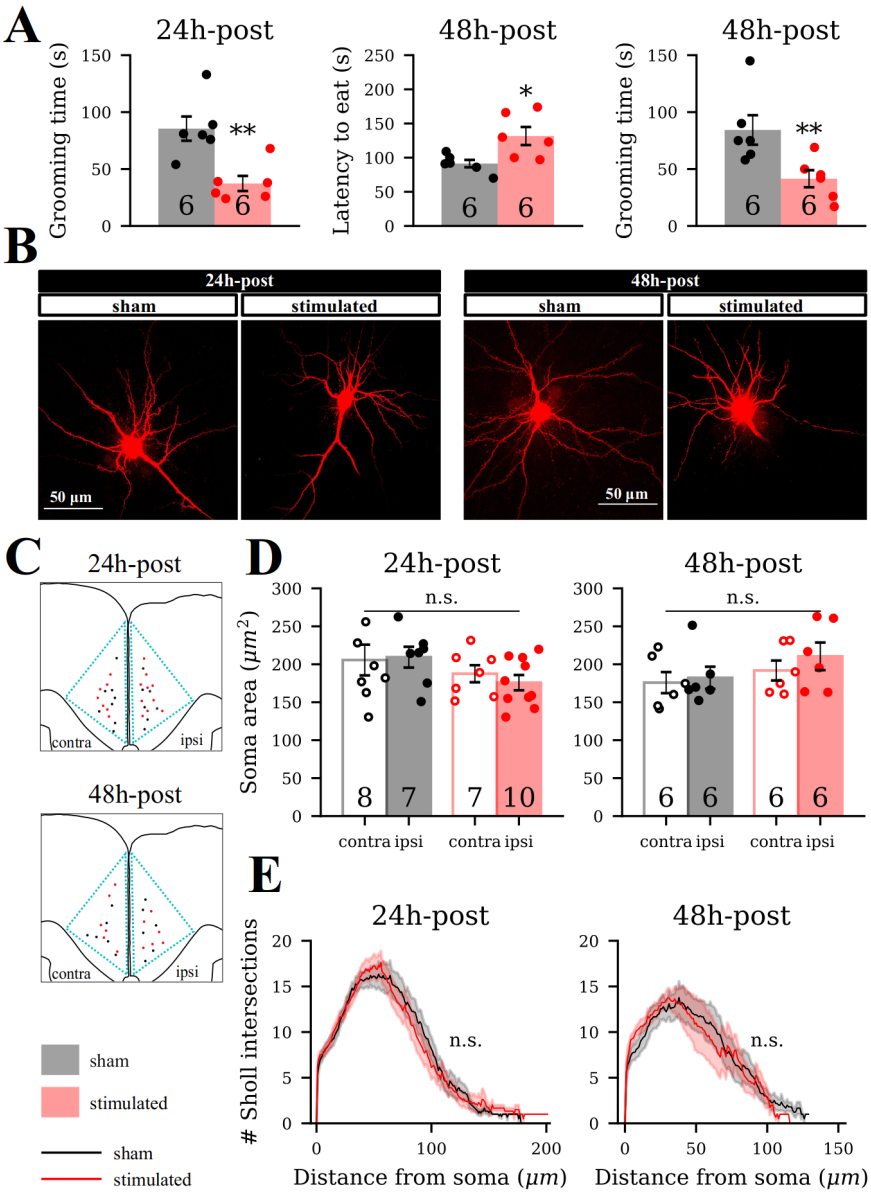

Figure 4: Neuronal dendritic tree structure was not drastically affected by the optogenetic stimulation at 24 h and 48 h. **A** Mice sacrificed at 24 h and 48 h for microinjection experiments showed depressive-like behavior in splash and NSF tests (for both batches, $N = 6$ for sham and $N = 6$ for the stimulated; $p = 0.006$, $p = 0.012$, and $p = 0.004$ respectively, Mann Whitney U test). **B** Representative example of neurons filled with red fluorescent dye. **C** Overall distribution of pyramidal neurons injected in layer 2-3 of ACC from both hemispheres for both batches. Black dots are from sham mice, and red dots are from the stimulated mice. For the 24 h-post group, we selected 32 well-injected neurons in total and 15 neurons were from sham mice; each mouse contributed 2.67 neurons on average (SD = 1.31). For the 48 h-post group, we selected 24 neurons in total and 12 neurons were from sham mice; each mouse contributed 2 neurons on average (SD = 2.12). **D** The soma size was not changed by stimulation (LMM). **E** Dendritic tree structure was not altered by stimulation (GLMM).

Optogenetic stimulation induced the opposite spine morphological changes at 24 h and 48 h

To further analyze morphological changes at dendritic level, we sampled several secondary to third level apical and basal dendritic segments from each neuron and did the 3D reconstruction of spines (Figure 5A-B). Besides spine density, we also evaluated the spine head volume and classified different types of spines such as filopodia, long-thin, stubby, and mushroom.

As shown in Figure 5C-D, the overall spine density was increased at 24 h ($p < 0.05$, LMM) and decreased at 48 h ($p < 0.05$, LMM) post-stimulation. The apical spine density showed the same tendency but the changes were not statistically significant; the basal dendrites showed significant spine density alterations ($p < 0.05$ and $p < 0.05$, LMM). Analysis by spine type suggested subtle changes in different spine types (Figure 5E-F). At 24 h, the spine density of filopodia and stubby type was increased in both apical ($p < 0.05$ and $p < 0.05$ respectively, LMM) and basal dendrites ($p < 0.05$ and $p < 0.05$, LMM). At 48 h, the spine density of long-thin type was reduced in apical dendrites ($p < 0.05$, LMM), while the stubby and mushroom type were reduced in basal dendrites ($p < 0.05$ and $p < 0.05$ respectively, LMM). These data suggested optogenetic stimulation triggered spinogenesis and spine retraction in both apical and basal dendrites at 24 h and 48 h post-stimulation respectively.

In addition, spine head volume data (Figure 5G-H) showed different regulation in apical and basal dendrites. At 24 h, the head volume distribution of long-thin spines in the apical dendrites was right-shifted to larger mean values by the optogenetic stimulation ($p < 0.05$, LMM) while no changes were detected in the head volume of basal dendrite spines. At 48 h, the spine head volume of mushroom spines in basal dendrites was left-shifted to smaller mean values by the optogenetic stimulation ($p < 0.05$, LMM), whereas the apical dendrites showed no significant difference. Our data suggested in addition to spine density changes, optogenetic stimulation induced spine enlargement and shrinkage at 24 h and 48 h post-stimulation respectively. The changes of overall spine density and

spine head volume align with the evolution of PSD-95.

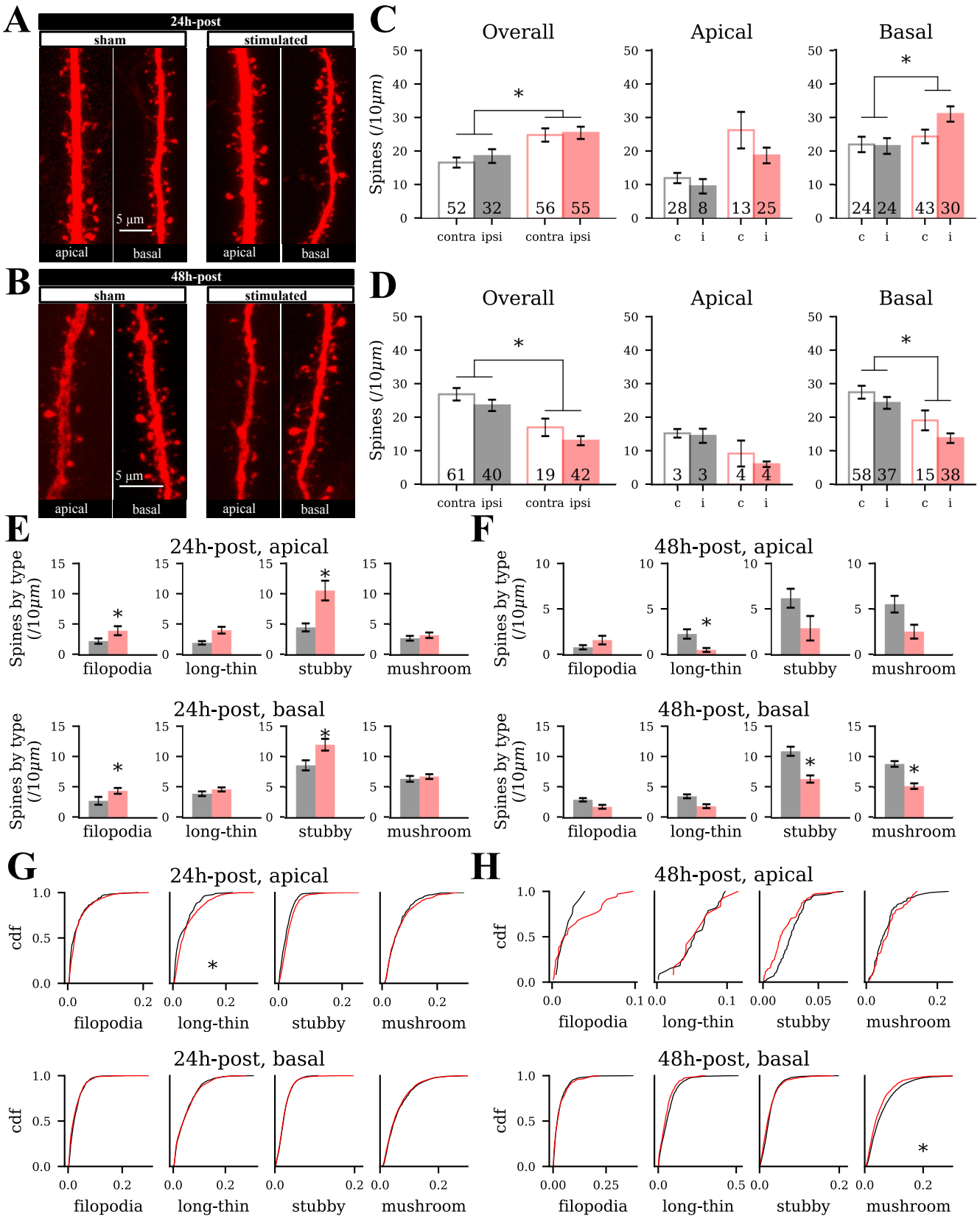

Figure 5: Spine density and head volume showed the opposite changes at 24 h and 48 h post-stimulation. **A-B** Representative example of filled dendritic segments. **C-D** Spine density at 24 h (84 dendritic segments from sham and 111 segments from stimulated mice) and 48 h (101 segments from sham and 61 segments from stimulated mice). **E-F** Spine density of each class. **G-H** Cumulative distribution of spine head volume. LMM was used for statistical analysis.

Glial responses were involved in homeostatic plasticity induced by the optogenetic stimulation

Glial cells were reported to participate in neural plasticity and maintain extracellular homeostasis (Dissing-Olesen et al. 2014; Haydon and Nedergaard 2015). It is then possible to observe simultaneous glial responses emerged with the alterations of spine morphology and synaptic proteins. Glial fibrillary acidic protein (GFAP) was stained as the markers for activated astrocytes (Hol and Pekny 2015), and ionized calcium-binding adaptor molecule 1 (IBA1) was stained for both inactive and active microglia (Ohsawa et al. 2004).

The fluorescent staining of GFAP was organized by distance and by time in Supplementary Figure 6-1. Our statistics analysis showed optic fiber implantation triggered astrocytes reactivation in both sham and stimulated mice, but the stimulation further enhanced the reactivation in the ipsilateral hemisphere throughout 48 h post-stimulation (Figure 6A-B). Similar results were observed with IBA1 staining (Supplementary Figure 6-2) as optogenetic stimulation induced significant enhancement of IBA1 expression at 24 h and 48 h post-stimulation ($p < 0.001$ and $p < 0.001$, GLMM) in the ipsilateral hemisphere and in the sections close to the optic fiber (Figure 6C-D). Since IBA1 labels microglia regardless of its activation state, the upregulation of IBA1 suggested microglia proliferation. Our data confirmed that optogenetic stimulation triggered astrocytes reactivation and microglia proliferation throughout 48 h post-stimulation.

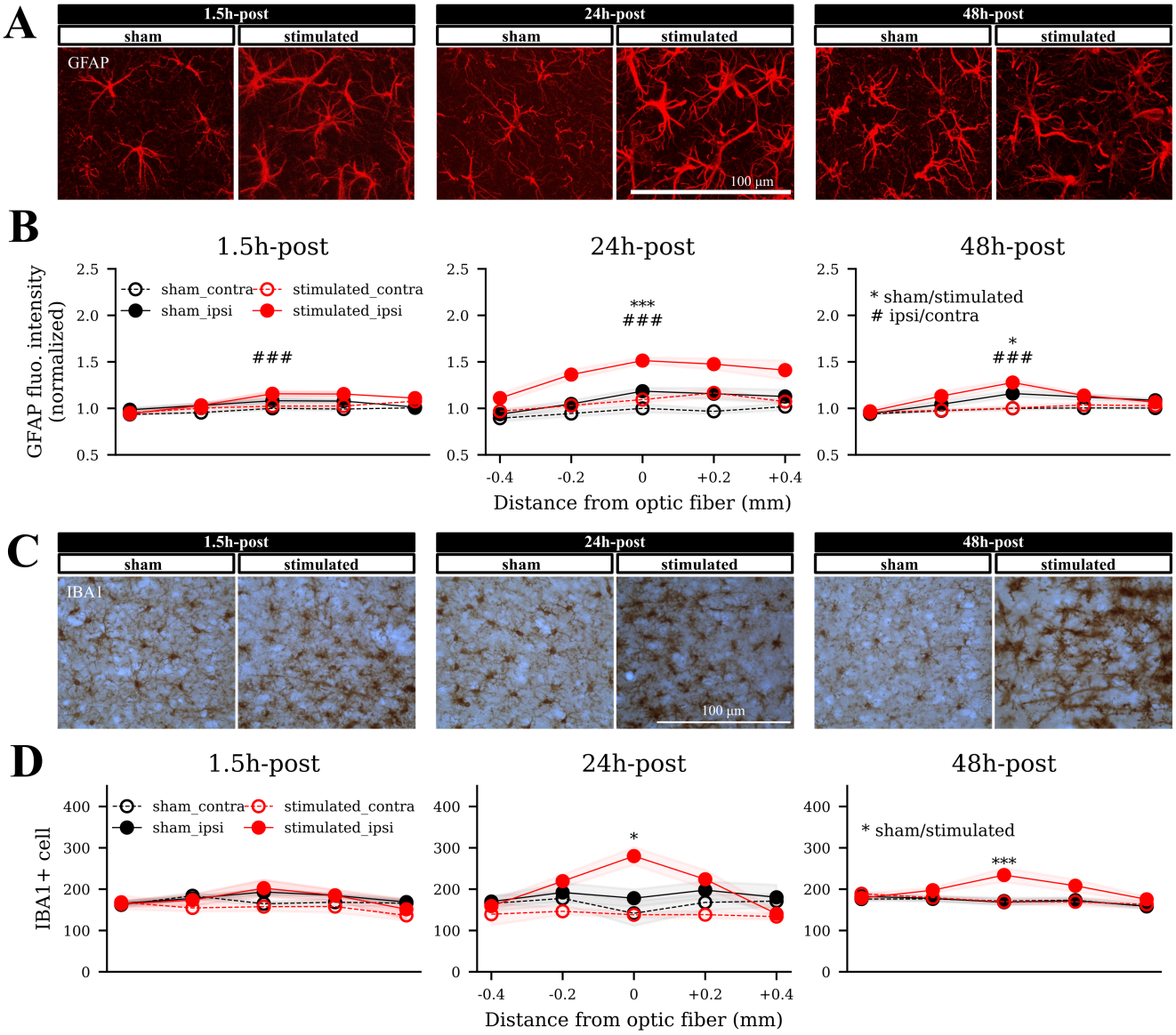

Figure 6: Expression of GFAP and IBA1 were upregulated by optogenetic stimulation at 24 h and 48 h post-stimulation. **A, C** Representative images of GFAP and IBA1 staining on the ipsilateral hemisphere of sections within 0.1 mm AP to the optic fiber from both sham and the stimulated mice. **B** The normalized GFAP fluorescent intensity at different time and distance. At 1.5 h, the main effects of side of stimulation were significant (99.5% CI = $[-0.0923, -0.0356]$, LMM). At 24 h, the main effects of optogenetic stimulation and side of stimulation were again significant (99.5% CI = $[0.0646, 0.399]$, 99.5% CI = $[-0.182, -0.0628]$ respectively); their interaction effects were also significant (99.5% CI = $[-0.264, -0.109]$). At 48 h , the main effects of stimulation, side of stimulation, and their interaction effects were significant (95% CI = $[0.009, 0.094]$, 99.5% CI = $[-0.115, -0.043]$, 95% CI = $[-0.079, -0.006]$ respectively). **D** The IBA1+ cell counting at different time and distance to the optic fiber. At 1.5 h, only the interaction between stimulation and side of stimulation were significant (95% CI = $[-0.188, -0.00016]$, GLMM). At 24 h, the main effect of optogenetic stimulation was significant (95% CI = $[0.025, 0.237]$); their interaction effects were also significant (99.5% CI = $[-0.533, -0.105)$. At 48 h , the main effects of optogenetic stimulation was significant (99.5% CI = $[0.073, 0.193]$); their interaction was also significant (99.5% CI = $[-0.208, -0.0369]$).

A computational model of stimulation-induced homeostatic structural plasticity

To achieve a clearer picture of the ongoing network remodeling dynamics in the current study, we interpolated the time course of synaptic protein expression and neural morphological changes within 48 h after four stimulation sessions (Figure 7A). The stimulation triggered immediate hyperactivity in ACC pyramidal neurons, as represented by c-Fos over-expression. Neural activity was restored to baseline at 24 h and 48 h. However, although neural activity was restored, we observed a delayed upregulation of synaptic proteins (VGLUT1 and PSD-95) and spine density at 24 h and a decrease to or below baseline at 48 h. These data suggest that the elevated synaptic proteins and spine density at 24 h do not contribute to sustaining high spontaneous neural activity. Three possibilities arise. (i) The upregulation of VGLUT1 and PSD-95 and spinogenesis failed to increase functional synaptic transmission among the stimulated pyramidal neurons. (ii) Optogenetic stimulation indeed increased the glutamatergic transmission, but additional mechanisms such as rapid E/I balance masked its effect on neural activity (Shu et al. 2003; Van Vreeswijk and Sompolinsky 1996; Zenke and Gerstner 2017). (iii) The upregulation of synaptic proteins and increase in spine number and volume are a consequence of firing rate homeostasis. Although we cannot directly reject options (i) and (ii) without electrophysiological recordings, it has indeed previously been shown that repetitive transcranial direct current stimulation (tDCS, 20 min $*$ 3 days) triggered enhanced synaptic transmission and increased spine density of pyramidal neurons 24 h after the stimulation in mice (Barbati et al. 2020). Besides, many previous studies have suggested that strength and morphology of excitatory synapses are homeostatically regulated (De Gois et al. 2005; Ehrlich et al. 2007; Konur et al. 2003; Turrigiano et al. 1998; Van Ooyen 2011) with or without changes of inhibitory synapses (Knott et al. 2002; Lenz et al. 2019) after activity perturbation. Therefore, it is highly possible that in our case optogenetic stimulation triggered homeostatic regulation.

The question now is which neuronal mechanism can account for the observed time

course. Inhibitory STDP, inhibitory plasticity, synaptic scaling, and the Bienenstock-Cooper-Munro (BCM) model are commonly known homeostatic rules complementing Hebbian plasticity. These rules do not include synapse rewiring. In some cases, enhanced spontaneous neural activity emerges with enhanced synaptic weight, which does not fit what we observed at 24 h post-stimulation (Lazar et al. 2009; Litwin-Kumar and Doiron 2014; Toyoizumi et al. 2014; Zenke and Gerstner 2017). We thus selected the model of homeostatic structural plasticity (HSP), which assumes structural changes regulated by firing rate homeostasis. We simulated an inhibition-dominated spiking neural network to represent ACC (Figure 7C), in which optogenetic stimulation was introduced to half of the excitatory population. Transient stimulation perturbed the neural activity and triggered synapse turnover as a result of homeostatic structural plasticity (blue curves in Figure 7C), as described in a previous publication (Lu et al. 2019). As a result of synaptic reorganization, the connectivity among the stimulated neurons remained elevated after stable firing rates were achieved (Figure 7D). In a repetition protocol based on our *in vivo* experiments, simulation results show that the connectivity among the stimulated neurons increased after each repetition. Within 48 h after the final stimulation (S4), the firing rate of the stimulated neurons rapidly returned to baseline. The connectivity, however, remained elevated and decayed only slowly (insets in Figure 7E). Although we could not differentiate stimulated and non-stimulated neurons in the mouse experiments, the neurons selected for morphological analysis were close to the optic fiber and, therefore, had a higher chance to be stimulated. The HSP model, thus, provided a fully consistent explanation for the observed c-Fos expression and spine morphology.

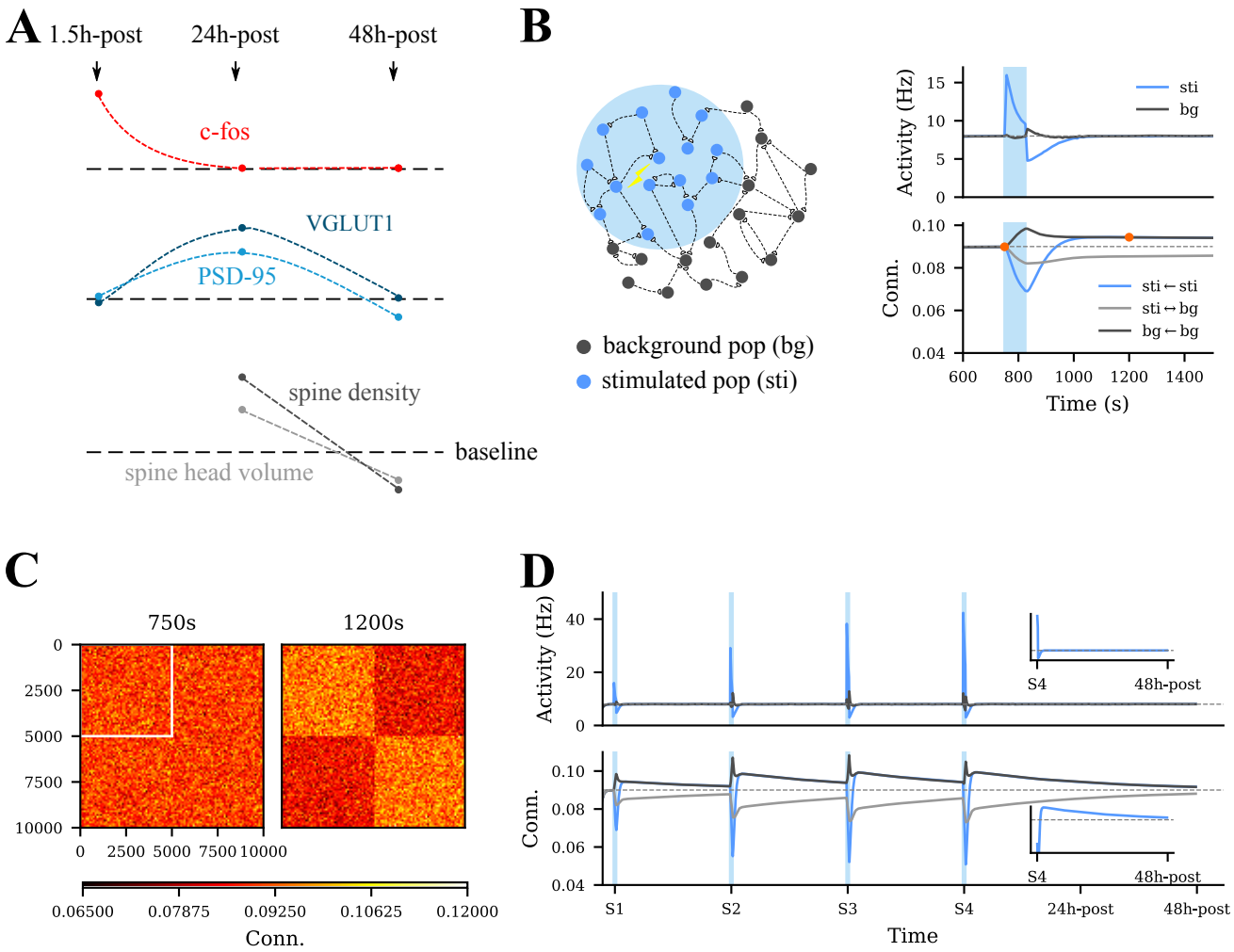

Figure 7: The homeostatic structural plasticity model. **A** The interpolated time course of the expression of c-Fos, VGLUT1, PSD-95 and spine morphology compared to sham (baseline). **B** Temporal evolution of neural activity and network connectivity in response to optogenetic stimulation. Light blue shaded areas indicate the stimulation period. Blue and dark gray curves in the upper panel represent the firing rate of stimulated and non-stimulated neurons. Blue, dark gray, and light gray curves in the lower panel represent the synaptic connectivity within or between populations. The blue and light gray curves finally coincided due to identical population sizes. **C** The connection matrix of all excitatory neurons at two time points before and after stimulation, labeled by orange dots in panel **B**. Columns are the presynaptic neurons, and rows are the postsynaptic neurons. Color indicates the average connectivity. The white square labels the intra-group connectivity of the stimulated neurons. **D** Repetitive optogenetic stimulation boosted the connectivity among the stimulated neurons. Small insets display the dynamics within 48 h after the last stimulation session.

Discussion

In the current study, we combined both mouse experiments and computer simulations to study structural plasticity. We first systematically investigated the neural activation and plastic responses of the neocortical region anterior cingulate cortex (ACC) after chronic optogenetic stimulation in an *in vivo* mouse model. We found that the activation of a subset of excitatory neurons in ACC over four consecutive days triggered substantial plastic alterations. In fact, the temporal profiles of specific molecular and morphological changes over 48 h post-stimulation were intertwined in a specific way. The expression of VGLUT1 and PSD-95, as well as the spine density and spine head volume, were above baseline at 24 h and restored to baseline or slightly below at 48 h. Intriguingly, although such changes seem to suggest altered synaptic transmission, neural activity estimated by c-Fos expression did not show any change at 24 h and 48 h. After neural activity has rapidly returned to baseline, synaptic protein expression and spine density undergoes a rise and a decay as compared to the control (Figure 8, red and blue curves). All things considered, it appears as if synaptic plasticity regulated by firing rate homeostasis can explain the time course of events described above quite well. In fact, we verified with the help of computer simulations that the homeostatic structural plasticity (HSP) model, in principle, recapitulates the observed biphasic dynamics Gallinaro et al. (2020); Gallinaro and Rotter (2018); Lu et al. (2019).

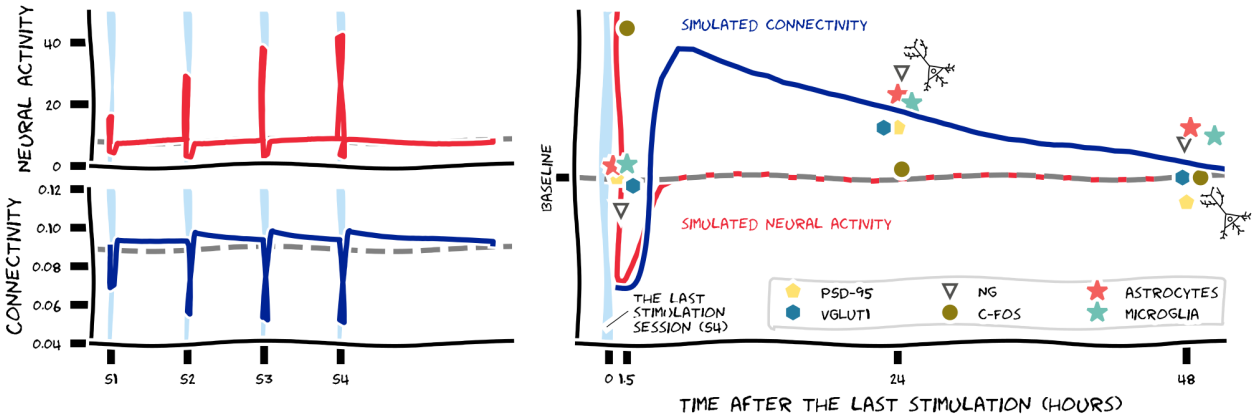

Figure 8: Joint summary of the results of mouse experiments and the computational model. Light blue shaded areas indicate four sessions of optogenetic stimulation (S1 to S4, 30 min per session). Red and blue curves represent the temporal profile of neural activity and connectivity of stimulated neurons, as predicted by the model. Colored symbols in the right panel represent the expression level of c-Fos, synaptic proteins, and glial markers, respectively. Measurements were made at 1.5 h, 24 h, and 48 h post-stimulation, shown are the values from stimulated mice relative to the corresponding sham group. For Neurogranin, we show its relative expression in dendrites. The gray dashed line represents the baseline. Symbols above or below the baseline indicate that values in stimulated mice are increased or decreased as compared to sham, respectively. The illustration of a neuron with dendrites and spines depicts that spine density and spine head volume were both increased at 24 h, but decreased at 48 h post-stimulation.

Our experiments elucidated how structural plasticity of pyramidal neurons evolves in time after optogenetic stimulation in the mouse experiments. Analysis of the expression of synaptic proteins clearly indicates that robust synaptic changes occurred at 24 h and 48 h after stimulation. VGLUT1 is the glutamate transporter protein that controls the quantal glutamate content of individual synaptic vesicles Fremeau et al. (2004); Wilson et al. (2005). Therefore, the upregulation and downregulation of VGLUT1 observed in our current study hints at a change of glutamate release in synapses, corresponding to the presynaptic strength accumulated over many neurons in a given tissue volume. PSD-95 is a scaffold protein in the postsynaptic density that organizes the distribution of AMPA receptors Chen et al. (2011); Zhang et al. (1999) and regulates postsynaptic strength. We observed similar biphasic changes in the expression of PSD-95 and VGLUT1 after stimulation. However, the expression of neurogranin, a calmodulin-binding protein exclusively expressed in the soma and dendrites of excitatory neurons Singec et al. (2004),

behaved differently. Optogenetic stimulation failed to trigger upregulation or downregulation of neurogranin, but changed somatic signal intensity over time. As neurogranin can translocate within pyramidal neurons upon synaptic stimulation from the cell plasma to the nucleus Garrido-García et al. (2009) or from the soma to the dendrites Huang et al. (2011), our data may suggest a translocation away from the soma in parallel with the upregulation of VGLUT1 and PSD-95. All these observations point to a biphasic regulation of synaptic strength within 48 h and an orchestrated regulation of presynaptic and postsynaptic plasticity after stimulation, as reported before by others Ehrlich et al. (2007); Letellier et al. (2019); Sanderson et al. (2020). The results of neural morphology analysis were in line with our observations in synaptic proteins. Optogenetic stimulation did not alter dendritic branching structure or soma size, as it was observed in the case of diseases Chidambaram et al. (2019). Rather, stimulation induced biphasic changes at the level of dendritic spines. The density and volume of spines in the stimulated pyramidal neurons increased at 24 h and slightly decreased at 48 h, as compared to controls. This is highly interesting, as spine volume correlates with synapse strength Matsuzaki et al. (2004) and PSD-95 clustering Cane et al. (2014). Increased spine density increases the chances to form new synapses. All things considered, we conclude that synaptic transmission and connectivity is increased at 24 h and restored to baseline at 48 h after stimulation.

Given the biphasic temporal profile of changes in synaptic proteins and dendritic spine morphology, we hypothesized that they might be a result of homeostatic regulation. In fact, the time evolution of synaptic protein expression reflects the accumulation of effects of all four stimulation sessions. The time course of PSD-95, for example, is around baseline at 1.5 h, upregulated at 24 h, and decayed slightly below baseline at 48 h after the last stimulation. Classical Hebbian plasticity depends on positive feedback, and it would systematically increase PSD-95 expression upon stimulation. Homeostatic plasticity, in contrast, depends on negative feedback, and it would at least transiently decrease the PSD-95 level. As the low level of PSD-95 immediately after the fourth stimulation is also 24 h after the third stimulation, a pure Hebbian mechanism is out of question, and a contribution of homeostatic control is likely (see Supplementary Figure 7-3 for a graphical

illustration of the argument). A second independent argument can be derived from the temporal profile of c-Fos expression. Indeed, the hyperactivity expected by optogenetic stimulation in pyramidal neurons is not visible 24 h and 48 h after stimulation, possibly because homeostatic regulation has brought it back to its set point. Although c-Fos expression is not a very accurate indicator of neural activity, other *in vivo* electrophysiological recordings did confirm the robust firing rate homeostasis in the cortex Pacheco et al. (2019). As a result, it seems possible that the observed changes in synaptic proteins and spine morphology reflect the dynamic process of homeostatic control to restore neural activity after activity perturbation. Theoretically, an alternative explanatory scheme may be linked to inhibitory plasticity Vogels et al. (2013, 2011), although we found no evidence for this in our data.

We proposed the model of homeostatic structural plasticity to explain the observed biphasic changes of spine morphology at 24 h and 48 h post-stimulation, when the neural activity indicated by c-Fos expression was already back at baseline. This model explains how neuronal firing rates are stabilized using structural plasticity linked with a homeostatic controller Butz and van Ooyen (2013); Butz et al. (2009); Van Ooyen (2011). We have previously shown in computer simulations how external stimulation can trigger cell assembly formation by deleting connections and forming new synapses controlled by firing rate homeostasis Gallinaro et al. (2020); Gallinaro and Rotter (2018); Lu et al. (2019). In computer simulations of the optogenetic experiment, we observed a very similar cell assembly formation process. Specifically, we showed that in this model the connectivity among stimulated neurons remained at a high level although the firing rate had already returned to baseline. Although we could not record the connectivity among the stimulated neurons in mouse ACC like we did in computer simulations, the changes of spine density in the pyramidal neurons sampled in the area close to the optic fiber served as a proxy and seemed to fit the computer simulations. Due to firing rate homeostasis, application and termination of the external stimulation should trigger slow homeostatic responses of opposite sign. Typical experiments, however, record a mix of changes occurring during perturbation and after perturbation, which may be of opposite sign. For instance, plas-

tic changes observed as a result of a persistent lesion or denervation occur during input deprivation. In contrast, plastic alterations observed after stimulation, as in the current study, are mixed on and off effects. So it is critical to use an experimental design that includes both phases and measure during time periods that are long enough to re-establish the neural activity homeostasis. In addition to spine turnover and spine density, specific changes in connectivity represent another crucial feature that influences network function. Although not the main focus of this study, we showed that astrocytes and microglia are also contributing to structural plasticity, but their activation has a different time course from that of synaptic proteins and spine morphology.

Our study also casts light on the relation between ACC hyperactivity, synaptic plasticity, and depressive-like behavior. ACC is a hub for negative affects, pain, and their comorbidity Humo et al. (2019). Chronic pain can induce hyperactivity and synaptic potentiation in ACC, along with anxiodepressive behavior in mice Koga et al. (2015); Sellmeijer et al. (2018). ACC hyperactivity artificially induced by optogenetic stimulation also generates depressive-like behavior in naive mice Barthas et al. (2017, 2015). It is unclear, however, whether changes in neuronal activity, spine morphology, and depressive-like behavior develop in parallel due to a common condition, or whether there are causal links between individual factors Gipson and Olive (2017). In our experiments, neural activity quickly decayed to baseline after stimulation, but the mice exhibited sustained depressive-like behavior, which can last for around two weeks after the stimulation was terminated Barthas et al. (2017). So the alterations in depressive-like behavior seem to always lag behind changes in ACC neural activity. This evidence suggests that depressive-like behavior may be mediated by persistent changes that depend on the accumulated effects of neural activity. On the other hand, we observed that synaptic plasticity (synaptic proteins and spine morphology) showed opposite transient changes during depressive behavior. As plasticity is tightly coupled to activity, it is likely that plasticity also mediates a link to behavior. Plasticity rules, either Hebbian or homeostatic, are activity-dependent and in turn regulate neural activity. So depending on its actual role in regulating neural activity, plasticity can either enhance ACC hyperactivity and exacerbate depressive symptoms, or

reduce hyperactivity and alleviate depressive symptoms. Furthermore, the apical and basal dendrites showed different morphological alterations in the experiments. As the apical dendrites of pyramidal neurons in ACC preferentially connect to the contralateral ACC, prefrontal cortex, amygdala, and other brain areas Fillinger et al. (2017), spinogenesis and spine head enlargement in the apical dendrites may point towards enhanced communication between ACC and other regions during the progression of depressive disorder.

Our joint experimental-theoretical efforts provide evidence that, in response to suprathreshold optogenetic excitation, neurons modulate their synaptic connectivity to restore neural activity in a homeostatic way. The homeostatic structural plasticity model was able to qualitatively explain the observed time course of neural activity and spine morphology. Further joint work is needed to capture the effects of activity perturbation on specific network connectivity and include functional aspects to structural plasticity models.

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Author contributions

HL, JG, CN, SR, and IY conceived the project and designed the experiments. HL, JG, and SR established the computer model. HL performed the network simulation and analysis. HL performed all the mice experiments, collected data, and performed the analysis. CN and IY helped with the experiments. IY proposed the quantification strategy. HL wrote the manuscript, and all the authors revised and approved the paper.

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